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A SURVEY ON FIXED POINT THEOREMS IN GENERALIZED CONVEX SPACES(Nonlinear Analysis and Convex Analysis)

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CITATION:

PARK, SEHIE. A SURVEY ON FIXED POINT THEOREMS IN GENERALIZED CONVEX SPACES(Nonlinear Analysis and Convex Analysis). 数理解析研究所講究録 2006, 1484: 124-133

ISSUE DATE:

2006-04

URL:

<http://hdl.handle.net/2433/58113>

RIGHT:

A SURVEY ON FIXED POINT THEOREMS IN GENERALIZED CONVEX SPACES

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ABSTRACT. We review some fixed point theorems which have appeared in our previous works [P1-11] on generalized convex spaces.

The concept of generalized convex spaces is a common generalization of various abstract convexities with or without linear structure and includes those of convex subsets of topological vector spaces, convex spaces of Lassonde, C -spaces due to Horvath, and many others. In the present paper, we review some fixed point theorems which have appeared mainly in our previous works [P1-11] on generalized convex spaces. Most of them are generalizations of well-known corresponding ones for topological vector spaces (t.v.s.).

1. Generalized convex spaces

A *generalized convex space* or a *G-convex space* $(Y, D; \Gamma)$ consists of a topological space Y , a nonempty set D , and a multimap $\Gamma : \langle D \rangle \multimap Y$ such that for each $A \in \langle D \rangle$ with cardinality $|A| = n + 1$, there exists a continuous function $\phi_A : \Delta_n \rightarrow \Gamma(A)$ such that $J \in \langle A \rangle$ implies $\phi_A(\Delta_J) \subset \Gamma(J)$, where $\langle D \rangle$ is the class of all nonempty finite subsets of D , Δ_n denotes the standard n -simplex with vertices $\{e_i\}_{i=0}^n$, and Δ_J the face of Δ_n corresponding to $J \in \langle A \rangle$; that is, if $A = \{a_0, a_1, \dots, a_n\}$ and $J = \{a_{i_0}, a_{i_1}, \dots, a_{i_k}\} \subset A$, then $\Delta_J = \text{co}\{e_{i_0}, e_{i_1}, \dots, e_{i_k}\}$.

We may write $\Gamma_A = \Gamma(A)$ and it is possible to assume $\Gamma_A = \phi_A(\Delta_n)$ for each $A \in \langle D \rangle$. A *G-convex space* $(X, D; \Gamma)$ with $X \supset D$ is denoted by $(X \supset D; \Gamma)$ and $(X; \Gamma) := (X, X; \Gamma)$. For a *G-convex space* $(X \supset D; \Gamma)$, a subset $Y \subset X$ is said to be *Γ -convex* if for each $N \in \langle D \rangle$, $N \subset Y$ implies $\Gamma_N \subset Y$. For details on *G-convex spaces* and examples, see [P1,4,5, PK1-6], where basic theory was extensively developed.

A *G-convex space* $(X, D; \Gamma)$ is called a *C-space* if each Γ_A is contractible (or more generally, n -connected for all $n \geq 0$) and, for each $A, B \in \langle D \rangle$, $A \subset B$ implies $\Gamma_A \subset \Gamma_B$. For $X = D$, this concept reduces to the one due to Horvath [H1,2].

We give here only a few examples of *G-convex spaces*:

2000 *Mathematics Subject Classification.* 47H04, 47H10, 52A07, 54C60, 54H25, 55M20.

Key words and phrases. The Schauder conjecture, Kakutani map, Fan-Browder map, approximable map, better admissible class of multimaps.

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Examples 1. [PM] Let $X = D = [0, 1)$ and $Y = D' = \mathbb{S}^1 = \{e^{2\pi it} : t \in [0, 1)\}$ in the complex plane \mathbb{C} . Let $f : X \rightarrow Y$ be a continuous function defined by $f(t) = e^{2\pi it}$. Define $\Gamma : \langle D' \rangle \multimap Y$ by

$$\Gamma_A = f(\text{co}(f^{-1}(A))) \quad \text{for } A \in \langle D' \rangle.$$

Then $(Y \supset D'; \Gamma)$ is a compact G -convex space. (More generally, it is known that any continuous image of a G -convex space is a G -convex space.) We note the following:

(1) \mathbb{S}^1 lacks the fixed point property. Moreover, \mathbb{S}^1 is an example of a compact C -space since each Γ_A is contractible. Therefore, it shows that the Schauder conjecture (that is, any compact convex subset of a t.v.s. has the fixed point property) does not hold for G -convex spaces.

(2) Note that, in $(Y \supset D'; \Gamma)$, singletons are Γ -convex; that is, $\Gamma_{\{y\}} = \{y\}$ for each $y \in D'$.

(3) $(Y, D; \Gamma)$ with $\Gamma : \langle D \rangle \multimap Y$ defined by

$$\Gamma_A = f(\text{co } A) \quad \text{for } A \in \langle D \rangle$$

is an example of a G -convex space satisfying $D \not\subset Y$.

Examples 2. Let $X = D = [0, 1]$ and $Y = D' = \mathbb{S}^1 = \{e^{2\pi it} : t \in [0, 1]\}$. Define f and Γ_A as in Examples 1. Then $(Y \supset D'; \Gamma)$ is a compact G -convex space.

(1) Note that $1 \in \mathbb{S}^1$ and that $\Gamma_{\{1\}} = \mathbb{S}^1$ is not contractible. Hence, $(Y \supset D'; \Gamma)$ is not a C -space.

(2) Moreover $\Gamma_{\{1\}} \neq \{1\}$. Therefore, in general, $\Gamma_{\{y\}} \neq \{y\}$ in a G -convex space.

Examples 3. Similarly, for $X = [0, 1) \times [0, 1)$ or $X = [0, 1] \times [0, 1]$, we can make the torus, the Möbius band, and the Klein bottle into compact G -convex spaces, as was noted by Horvath [H1].

Several authors modified our definition of G -convex spaces and claimed that theirs are general than ours. All of them failed to give any proper meaningful example justifying their claims.

The following is known:

Theorem 1. [PM] Let X be a compact Hausdorff uniform space with a basis \mathcal{U} of the uniformity and $f : X \rightarrow X$ a continuous map. Then f has a fixed point if and only if for any $V \in \mathcal{U}$, $\text{Gr}(f) \cap \bar{V} \neq \emptyset$.

2. Fan-Browder maps

A *multimap* (simply, a *map*) $T : X \multimap Y$ is a function from X into the power set 2^Y of Y . $T(x)$ is called the *value* of T at $x \in X$ and $T^-(y) := \{x \in X : y \in T(x)\}$ the *fiber* of T at $y \in Y$. Let $T(A) := \bigcup \{T(x) : x \in A\}$ for $A \subset X$.

For topological spaces X and Y , a map $T : X \multimap Y$ is said to be *closed* if its *graph* $\text{Gr}(T) := \{(x, y) : x \in X, y \in T(x)\}$ is closed in $X \times Y$, and *compact* if its range $T(X)$ is contained in a compact subset of Y .

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A map $T : X \multimap Y$ is said to be *upper semicontinuous* (u.s.c.) if for each closed set $B \subset Y$, the set $T^-(B) = \{x \in X : T(x) \cap B \neq \emptyset\}$ is a closed subset of X ; *lower semicontinuous* (l.s.c.) if for each open set $B \subset Y$, the set $T^-(B)$ is open; and *continuous* if it is u.s.c. and l.s.c. Note that a compact closed multimap is u.s.c. and compact-valued; and that every u.s.c. map with closed values is closed.

A multimap with nonempty convex values and open fibers is called a *Browder map*. The well-known *Fan-Browder fixed point theorem* states that a Browder map T from a compact convex subset X of a t.v.s. into itself has a fixed point [Br].

From the celebrated KKM theorem, we obtained the following general form of the Fan-Browder fixed point theorem:

Theorem 2. [P4,8] *Let $(X, D; \Gamma)$ be a G -convex space, and $S : D \multimap X$, $T : X \multimap X$ multimaps. Suppose that*

- (1) $S(z)$ is open [resp. closed] for each $z \in D$;
- (2) for each $y \in X$, $M \in \langle S^-(y) \rangle$ implies $\Gamma_M \subset T^-(y)$; and
- (3) $X = S(N)$ for some $N \in \langle D \rangle$.

Then T has a fixed point $x_0 \in X$; that is, $x_0 \in T(x_0)$.

In [P8], this is applied to obtain various forms of known Fan-Browder type theorems, the Ky Fan intersection theorem, and the Nash equilibrium theorem.

The following is the dual form of Theorem 2:

Theorem 3. [P7] *Let $(X, D; \Gamma)$ be a G -convex space and $S : X \multimap D$, $T : X \multimap X$ maps such that*

- (1) for each $x \in X$, $M \in \langle S(x) \rangle$ implies $\Gamma_M \subset T(x)$;
- (2) $S^-(z)$ is open [resp. closed] for each $z \in D$; and
- (3) $X = \bigcup \{S^-(z) : z \in N\}$ for some $N \in \langle D \rangle$.

Then T has a fixed point $x_0 \in X$.

From Theorem 3, we have the following:

Theorem 4. [P10] *Let $(X \supset D; \Gamma)$ be a G -convex space and $A : X \multimap X$ a multimap such that $A(x)$ is Γ -convex for each $x \in X$. If there exist $z_1, z_2, \dots, z_n \in D$ and nonempty open [resp. closed] subsets $G_i \subset A^-(z_i)$ for $i = 1, 2, \dots, n$ such that $X = \bigcup_{i=1}^n G_i$, then A has a fixed point.*

Theorem 5. [P7] *Let $(X, D; \Gamma)$ be a G -convex space and $S : X \multimap D$, $T : X \multimap X$ maps such that*

- (1) for each $x \in X$, $M \in \langle S(x) \rangle$ implies $\Gamma_M \subset T(x)$; and
- (2) $X = \bigcup \{\text{Int } S^-(z) : z \in N\}$ for some $N \in \langle D \rangle$.

Then T has a fixed point.

From Theorems 2-5, most of popular variations or generalizations of the Fan-Browder theorem (in the forms of the compact or so-called non-compact versions) can be deduced; see [P7,8,10].

3. Φ -spaces and compact Φ -maps

For a topological space X and a G -convex space $(Y, D; \Gamma)$, a multimap $T : X \multimap Y$ is called a Φ -map provided that there exists a multimap $S : X \multimap D$ satisfying

- (a) for each $x \in X$, $M \in \langle S(x) \rangle$ implies $\Gamma_M \subset T(x)$; and
- (b) $X = \bigcup \{ \text{Int } S^-(y) : y \in D \}$.

A G -convex space $(Y, D; \Gamma)$ is called a Φ -space if Y is a Hausdorff uniform space and for each entourage V there exists a Φ -map $T : Y \multimap Y$ such that $\text{Gr}(T) \subset V$. This concept is originated from Horvath [H1], where a number of examples are given.

Theorem 6. [P1] *If $(Y, D; \Gamma)$ is a Φ -space, then any compact continuous function $g : Y \rightarrow Y$ has a fixed point.*

Recall that a nonempty convex subset X of a t.v.s. E is said to be *locally convex* (in the sense of Krauthausen) if for every $x \in X$ there exists a basis $\mathcal{V}(x)$ of neighborhoods of x such that every $V \in \mathcal{V}(x)$ is convex.

It is easily checked that every locally convex subset X is a Φ -space $(X; \Gamma)$ with $\Gamma_A = \text{co } A$ for $A \in \langle X \rangle$. Therefore, Theorem 6 works when X is a locally convex subset of a Hausdorff t.v.s. or X is a convex subset of a locally convex Hausdorff t.v.s.

For C -spaces, Theorem 6 reduces to Horvath [H1, Theorem 4.4], where some examples of Φ -spaces and applications of Theorem 6 were given.

A *G -convex uniform space* $(X \supset D; \Gamma)$ is a G -convex space such that D is dense in X and (X, \mathcal{U}) is a Hausdorff uniform space, where \mathcal{U} is a basis of the uniformity consisting of symmetric entourages.

A *locally G -convex space* is a G -convex uniform space $(X \supset D; \Gamma)$ with a basis \mathcal{U} such that for each $U \in \mathcal{U}$ and each $x \in X$,

$$U[x] = \{x' \in X : (x, x') \in U\}$$

is Γ -convex.

Lemma 1. [P6] *A locally G -convex space $(X \supset D; \Gamma)$ is a Φ -space.*

An *LG-space* is a G -convex uniform space $(X \supset D; \Gamma)$ with a basis \mathcal{U} such that for each $U \in \mathcal{U}$, $U[C] := \{x \in X : C \cap U[x] \neq \emptyset\}$ is Γ -convex whenever $C \subset X$ is Γ -convex.

For a C -space $(X; \Gamma)$, the concept of *LG-spaces* reduces to that of *LC-spaces* due to Horvath [H1, 2].

Lemma 2. [P6] *Every LG-space $(X \supset D; \Gamma)$ is a locally G -convex space if $\Gamma_{\{x\}} = \{x\}$ for each $x \in D$.*

A C -space $(X; \Gamma)$ is an *LC-metric space* if X is equipped with a metric d such that for any $\varepsilon > 0$, the set $\{x \in X : d(x, A) < \varepsilon\}$ is Γ -convex whenever A is Γ -convex in X and open balls in (X, d) are Γ -convex.

Examples 4. The G -convex spaces $(Y \supset D'; \Gamma)$ in Examples 1 and 2 are not Φ -spaces because of Theorem 6. Moreover, in view of Lemmas 1 and 2, they are neither locally G -convex nor an *LG-space*. Note that in these examples, a neighborhood of $1 \in \mathbb{S}^1$ is not Γ -convex.

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In 1990, Ben-El-Mechaiekh raised the following problem (see [P2]): Does the Fan-Browder fixed point theorem hold if we assume the map T is compact instead of the compactness of its domain X ?

This is still open. The following are general forms of partial solutions:

Theorem 7. [P2] *Let E be a Hausdorff t.v.s. whose nonempty convex subsets have the fixed point property for compact continuous single-valued selfmaps. Let X be a nonempty convex subset of E and $T : X \multimap X$ a Φ -map. If T is compact, then T has a fixed point.*

Theorem 8. [P1,2] *Let $(Y, D; \Gamma)$ be a paracompact C -space. If it is also a Φ -space, then any compact Φ -map $T : Y \multimap Y$ has a fixed point.*

Theorem 9. [P2] *Let $(X; \Gamma)$ be a Hausdorff G -convex space, and $T : X \multimap X$ a Φ -map. If T is compact, then T^n has a fixed point for $n \geq 2$.*

Theorem 10. [P2,9] *Let $(X \supset D; \Gamma)$ be a paracompact LC -space such that $\Gamma_{\{x\}} = \{x\}$ for all $x \in D$. Then any compact Φ -map $T : X \multimap X$ has a fixed point.*

Theorem 11. [P9] *Let $(X; \Gamma)$ be a paracompact LC -space such that $\Gamma_{\{x\}} = \{x\}$ for all $x \in X$, Y a compact LC -metric subset of X , and $Z \subset X$ with $\dim_X Z \leq 0$. Let $T : X \multimap Y$ be a l.s.c. map with closed values such that $T(x)$ is Γ -convex for $x \notin Z$. Then T has a fixed point.*

In [P3], further fixed point theorems for l.s.c. multimaps in LC -metric spaces are given.

4. Kakutani maps

Usually, an u.s.c. multimap with nonempty closed convex values is called a *Kakutani map* within the category of t.v.s.

We have the following fixed point theorem for general Kakutani type maps defined on particular types of G -convex spaces:

Theorem 12. [P9] *Let $(X \supset D; \Gamma)$ be an LG -space and $T : X \multimap X$ a compact u.s.c. multimap with closed Γ -convex values. Then T has a fixed point $x_0 \in X$.*

For a single-valued map, Theorem 12 reduces to the following:

Corollary 12.1. [P9] *Let $(X \supset D; \Gamma)$ be an LG -space such that $\Gamma_{\{x\}} = \{x\}$ for all $x \in D$. Then any compact continuous function $f : X \rightarrow X$ has a fixed point.*

In view of Lemmas 1 and 2, this is also a simple consequence of Theorem 6.

Let $(X \supset D; \Gamma)$ be a G -convex uniform space with a basis \mathcal{U} and K a nonempty subset of X . We say that K is of the *Zima type* [PK6] whenever for every $V \in \mathcal{U}$ there exists a $U \in \mathcal{U}$ such that for every $A \in \langle D \rangle$ and every Γ -convex subset M of K the following implication holds:

$$M \cap U[z] \neq \emptyset, \forall z \in A \Rightarrow M \cap V[u] \neq \emptyset, \forall u \in \Gamma_A,$$

where $U[z] = \{x \in X : (z, x) \in U\}$.

Lemma 3. [PK6] *For an LG-space $(X \supset D; \Gamma)$, any nonempty subset K of X is of the Zima type.*

In view of Lemma 3, the following generalizes Theorem 12.

Theorem 13. [PK6] *Let $(X \supset D; \Gamma)$ be a G -convex uniform space and $T : X \multimap X$ a compact u.s.c. map with nonempty closed Γ -convex values. If $T(X)$ is of the Zima type, then T has a fixed point $x_* \in X$.*

5. Better admissible maps

Let $(X, D; \Gamma)$ be a G -convex space and Y a topological space. We define the better admissible class \mathfrak{B} of multimaps from X into Y as follows [P4]:

$F \in \mathfrak{B}(X, Y) \iff F : X \multimap Y$ is a map such that for any $N \in \langle D \rangle$ with $|N| = n + 1$ and any continuous function $p : F(\Gamma_N) \rightarrow \Delta_n$, the composition

$$\Delta_n \xrightarrow{\phi_N} \Gamma_N \xrightarrow{F|_{\Gamma_N}} F(\Gamma_N) \xrightarrow{p} \Delta_n$$

has a fixed point. Note that Γ_N can be replaced by the compact set $\phi_N(\Delta_n)$.

We give some subclasses of \mathfrak{B} as follows [P4, PK1,3]:

For topological spaces X and Y , an admissible class $\mathfrak{A}_c^\kappa(X, Y)$ of maps $F : X \multimap Y$ is one such that, for each nonempty compact subset K of X , there exists a map $G \in \mathfrak{A}_c(K, Y)$ satisfying $G(x) \subset F(x)$ for all $x \in K$; where \mathfrak{A}_c consists of finite compositions of maps in a class \mathfrak{A} of maps satisfying the following properties:

- (i) \mathfrak{A} contains the class \mathbb{C} of (single-valued) continuous functions;
- (ii) each $T \in \mathfrak{A}_c$ is u.s.c. with nonempty compact values; and
- (iii) for any polytope P , each $T \in \mathfrak{A}_c(P, P)$ has a fixed point, where the intermediate spaces are suitably chosen.

Here, a polytope P is a homeomorphic image of a standard simplex. There are lots of examples of \mathfrak{A} and \mathfrak{A}_c^κ .

Subclasses of the admissible class \mathfrak{A}_c^κ are classes of continuous functions \mathbb{C} , the Kakutani maps \mathbb{K} (with convex values and codomains are convex spaces), Browder maps, Φ -maps, selectionable maps, locally selectionable maps having convex values, the Aron-szajn maps \mathbb{M} (with R_δ values), the acyclic maps \mathbb{V} (with acyclic values), the Powers maps \mathbb{V}_c (finite compositions of acyclic maps), the O'Neill maps \mathbb{N} (continuous with values of one or m acyclic components, where m is fixed), the u.s.c. approachable maps \mathbb{A} (whose domains and codomains are uniform spaces), admissible maps of Górniewicz, σ -selectionable maps of Haddad and Lasry, permissible maps of Dzedzej, the class \mathbb{K}_c^+ of Lassonde, the class \mathbb{V}_c^+ of Park et al., u.s.c. approximable maps of Ben-El-Mechaiekh and Idizk, and many others.

Note that for a subset X of a t.v.s. and any space Y , an admissible class $\mathfrak{A}_c^\kappa(X, Y)$ is a subclass of $\mathfrak{B}(X, Y)$. Some examples of maps in \mathfrak{B} not belonging to \mathfrak{A}_c^κ were known. Note that the connectivity map due to Nash and Girolo is such an example.

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For a particular type of G -convex spaces, we established fixed point theorems for the class \mathfrak{B} :

Theorem 14. [P4] *Let $(X, D; \Gamma)$ be a Φ -space and $F \in \mathfrak{B}(X, X)$. If F is closed and compact, then F has a fixed point.*

Note that Theorem 14 generalizes Theorem 6.

For a non-closed map, we have the following:

Corollary 14.1. *Let $(X, D; \Gamma)$ be a compact Φ -space and $F \in \mathfrak{A}_c^r(X, X)$. Then F has a fixed point.*

Since a locally G -convex space is a Φ -space by Lemma 1, we have

Corollary 14.2. *Let $(X \supset D; \Gamma)$ be a locally G -convex space. Then any closed compact map $F \in \mathfrak{B}(X, X)$ has a fixed point.*

Similarly, by Lemma 2, we have

Corollary 14.3. *Let $(X \supset D; \Gamma)$ be an LG -space such that $\Gamma_{\{x\}} = \{x\}$ for each $x \in D$. Then any closed compact map $F \in \mathfrak{B}(X, X)$ has a fixed point.*

For topological spaces X and Y , we adopt the following [PK1]:

$F \in \mathbb{V}(X, Y) \iff F : X \multimap Y$ is an acyclic map; that is, an u.s.c. multimap with compact acyclic values.

$F \in \mathbb{V}_c(X, Y) \iff F : X \multimap Y$ is a finite composition of acyclic maps where the intermediate spaces are topological.

It is known that $\mathbb{V}_c(X, Y) \subset \mathfrak{B}(X, Y)$ whenever X is a G -convex space, and that any map in \mathbb{V}_c is closed.

Corollary 14.4. *Let $(X, D; \Gamma)$ be a Φ -space. Then any compact map $F \in \mathbb{V}_c(X, X)$ has a fixed point.*

6. Approximable maps

In this section, all spaces are assumed to be Hausdorff.

Recently, Ben-El-Mechaiekh *et al.* [B, BC] introduced the class \mathbf{A} of approachable multimaps as follows:

Let X and Y be uniform spaces (with respective bases \mathcal{U} and \mathcal{V} of symmetric entourages). A multimap $T : X \multimap Y$ is said to be *approachable* whenever T admits a continuous W -approximative selection $s : X \rightarrow Y$ for each W in the basis \mathcal{W} of the product uniformity on $X \times Y$; that is, $\text{Gr}(s) \subset W[\text{Gr}(T)]$, where

$$W[A] := \bigcup_{z \in A} W[z] = \{z' \in X \times Y : W[z'] \cap A \neq \emptyset\}$$

for any $A \subset X \times Y$, and

$$W[z] := \{z' \in X \times Y : (z, z') \in W\}$$

for $z \in X \times Y$.

A multimap $T : X \multimap Y$ is said to be *approximable* if its restriction $T|_K$ to any compact subset K of X is approachable.

Note that an approachable map is always approximable. Recall that Ben-El-Mechaiekh et al. [B, BC] established a large number of properties and examples of approachable or approximable maps.

We denote $F \in \mathbf{A}(X, Y)$ if $F : X \multimap Y$ is approachable.

The following two lemmas are [BC, Lemmas 2.4 and 4.1], respectively.

Lemma 4. *Let (X, \mathcal{U}) , (Y, \mathcal{V}) , (Z, \mathcal{W}) be three uniform spaces, with Z compact, and let $\Psi : Z \multimap X$, $\Phi : X \multimap Y$ be two u.s.c. closed-valued approachable maps. Then so is their composition $\Phi \circ \Psi$.*

Lemma 5. *If X is a nonempty convex subset of a locally convex t.v.s. and if $\Phi \in \mathbf{A}(X, X)$ is closed and compact, then Φ has a fixed point.*

From Lemmas 4 and 5, we show that certain approachable maps are better admissible if their domains are G -convex spaces as follows:

Lemma 6. [P6] *Let $(X \supset D; \Gamma)$ be a G -convex uniform space and (Y, \mathcal{V}) a uniform space. If $F \in \mathbf{A}(X, Y)$ is closed and compact, then $F \in \mathbf{B}(X, Y)$.*

From Theorem 14 and Lemma 6, we have

Theorem 15. [P6] *Let $(X \supset D; \Gamma)$ be a Φ -space and $F \in \mathbf{A}(X, X)$. If F is closed and compact, then F has a fixed point.*

Examples 5. We give some examples of approachable maps $T : X \multimap Y$ as follows:

- (1) Any selectable multimap is approximable.
- (2) A locally selectable map T with convex values is approximable whenever Y is a convex subset of a t.v.s.
- (3) An u.s.c. map T with nonempty convex values is approachable whenever X is paracompact and Y is a convex subset of a locally convex t.v.s.
- (4) An u.s.c. map T with nonempty compact contractible values is approachable whenever X is a finite polyhedron.
- (5) An u.s.c. map T with nonempty compact values having trivial shape (that is, contractible in each neighborhood in Y) is approachable whenever X is a finite polyhedron.

For (1) and (2), see [P11]; and for (3)-(5), see [B].

The following is due to Ben-El-Mechaiekh et al. [BC, Proposition 3.9]:

Lemma 7. *Let (X, \mathcal{U}) and (Y, \mathcal{V}) are uniform spaces. If either*

- (i) *X is paracompact and $(Y; \Gamma)$ is an LC-space; or*
- (ii) *X is compact and $(Y; \Gamma)$ is an LG-space,*

then every u.s.c. map $F : X \multimap Y$ with nonempty Γ -convex values is approachable; that is, $F \in \mathbf{A}(X, Y)$.

Note that Lemma 7(i) generalizes Examples 5(3).

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In our previous work [P6], (ii) is incorrectly stated and causes some incorrect statements. For example, [P6, Theorem 4] should be stated for LG -spaces as in Theorem 12.

From Lemmas 6 and 7, we have the following correction of [P4, Lemma 4.5]:

Lemma 8. *Let $(X \supset D; \Gamma)$ be a compact LG -space. Then any u.s.c. map $F : X \multimap X$ with nonempty closed Γ -convex values belongs to $\mathfrak{B}(X, X)$.*

Consequently, correct forms of [P4, Corollary 4.7 and Theorem 4.8] are Theorem 12 and Corollary 14.1, respectively, in the present paper.

We add two types of new multimaps in the class \mathfrak{B} :

Lemma 9. *Let $(X, D; \Gamma)$ be a G -convex space and $F : X \multimap X$ be an u.s.c. map such that either*

- (i) *F has nonempty compact contractible values; or*
- (ii) *F has nonempty compact values having trivial shape,*

then $F \in \mathfrak{B}(X, X)$.

Proof. For any $N \in \langle D \rangle$ with $|N| = n + 1$ and any continuous function $p : F(\Gamma_N) \rightarrow \Delta_n$, consider the composition

$$\Delta_n \xrightarrow{\phi_N} \Gamma_N \xrightarrow{F|_{\Gamma_N}} F(\Gamma_N) \xrightarrow{p} \Delta_n.$$

Note that $(F|_{\Gamma_N}) \circ \phi_N$ is an u.s.c. multimap having values of the type (i) or (ii) and defined on a finite polyhedron Δ_n . Therefore $p \circ (F|_{\Gamma_N}) \circ \phi_N$ is approachable by Lemma 4, and has a fixed point by Lemma 5. This completes our proof.

From Theorem 14 and Lemma 9, we have

Theorem 16. [P4] *Let $(X, D; \Gamma)$ be a Φ -space and $F : X \multimap X$ be a map such that all of its values are either (i) nonempty contractible or (ii) nonempty and of trivial shape. If F is closed and compact, then F has a fixed point.*

Note that Case (i) of Theorem 16 is a consequence of Corollary 14.4. In the category of t.v.s., Theorem 16(i) holds for Kakutani maps since convex values are contractible. But, for G -convex spaces, Γ -convex values are only known to be connected and that is why we need Lemma 7.

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